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The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk

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ABSTRACT

The installation and operation of systems that exploit solar energy through photovoltaic conversion, recently promoted in some European countries by new sell-back tariffs, is a relevant transformation of the territory for various reasons (land use, elimination of the existing vegetation, visual impact on the components of the landscape, microclimate change, glare from the reflection of the direct sunlight). The weak energy intensity of the solar source coupled with the low conversion efficiency of the photovoltaic cells, make the physical dimensions of such systems relevant and, with them, also the environmental, territorial and landscape impacts that basically depend on the physical extent of the system. If it is well known that an incentive to the exploitation of renewable sources is one of the features of the policy of land conservation, including the one of the protected areas, at the same time the concerns of local communities and governments about the environmental, territorial and landscape impacts of this technology are increasing rapidly.

Given this picture, this work is intended to clarify the territorial impacts of the ground mounted photovoltaic systems. Later, the paper concentrates on a specific impact, which is the assessment of the risk of glare by reflection of direct sunlight from the surfaces of photovoltaic modules. The methodologies that can be used to assess this impact and the outcomes of an evaluation carried out for a 5000 m^2 PV system currently designed on a hilly territory in Italy are presented.

Contents

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Nomenclature

n	normal to the PV module
β_S	solar altitude
Φ	PV module orientation (from south, positive toward east)
Φ_S	solar azimuth (from south, positive toward east)
$\sum$	PV module tilt
Ξ	hillside tilt

1. Introduction

This work starts from the remark that the installation and operation of systems that exploit solar energy through photovoltaic (PV) conversion represent an important form of landscape transformation. In fact, the energy intensity of the solar source, even if uniformly distributed across the territory, is relatively weak and, together with the low conversion efficiencies of the photovoltaic cells, this results in relevant physical dimensions of such systems and, with that, relevant impacts that depend on the extension on the territory. Recently, both factors that have played a relevant role in the spread of the PV technology, and factors that have given rise to some concerns about the PV technology in local governments and communities, have grown up.

As regards the first set of factors, among the technologies to exploit renewable energy sources, there has been a great development of the solar photovoltaic in many European countries. The European energy policies are steadily directing the exploitation of renewable energy towards a massive use of photovoltaic systems, and in Italy the decree 19 February 2007 of the Ministry of the Economic Development has prompted a new interest in this technology.

As regards the second set of factors, even if it is well known that the incentive to the exploitation of renewable sources is one of the features of the policy of land conservation, including the one of protected areas [1], at the same time concerns of the collectivity and local governments about environmental, territorial and landscape impacts of this technology frequently hinder the siting decision process of such plants.

This is the case of private investors that have to face the particularly strict requirements of local administrations on the assessment of the environmental impact of a PV system, or the case of public administrators that are seeking for guidelines that prevent an unruled spreading of the PV technology over their territory, especially in case of historic sites and rural or mountain villages.

Similar problems were outlined by other researchers: Zoellner et al. [2] remarked that even if at a general level a considerable support for renewable energy policy exists, at a local level many residents feel that a renewable energy system may limit their quality of life for some reasons as the change of the landscape or the noise. This is why further research activity on the social acceptance of renewable energy at community level is of the greatest importance and is currently being developed. Wüstenhagen et al. [3] provide a general introduction on this subject.

2. Purpose of the work

For the reasons stated above, a sort of trade-off between contradictory requirements can be identified, and given this picture, this work aims at clarifying some of the territorial and landscape impacts of the PV systems and suggesting assessment procedures and tools that can be used.

First, the reasons of the rapid grow of photovoltaic systems and the assessment of the physical dimension and characteristics of this technology are addressed, then a literature review on the studies about the environmental impacts of photovoltaic is presented in order to ascertain to what degree the land use and the landscape impacts of PV were studied. It can be deduced that PV impacts were especially assessed by means of energy and environmental quantitative indicators, and this is the reason why the proposal of a list of the territorial and landscape impacts of photovoltaic is later presented and discussed.

In the second part of the paper, a specific impact, that is the glare risk from reflection of direct sunlight, is addressed. Methodologies to carry out the impact evaluation are presented and applied to a case study of a PV system of about 5000 m^2 currently planned on a hilly territory in Italy.

3. The Italian regulatory framework and the effects on the photovoltaic market

Even if the cost of photovoltaic modules dropped dramatically in recent years, PV technology still requires public funding in order to ensure its economic feasibility. This is why a series of programs promoting the development of this technology were carried out by the Italian Ministry of the Environment and – in addition to the energy and environmental benefits – a reduction in the installation cost, similarly to what happened in Germany in the past years, was also obtained. The first photovoltaic technology incentives in Italy were designed according to a *subsidy grant* scheme. This was the mechanism, for example, of the PV Roofs Program, launched in 2001 for the installation of PV systems integrated into buildings and grid connected, which had the merit of launching a market that before was practically nonexistent in Italy. A perspective on the Italian energy policy for photovoltaic promotion can be found in [4]. In this way, however, there was no guarantee that the system will have operated correctly and therefore it was not sure if the system had achieved its environmental benefits over the life time. In contrast to the first mechanism, in the financial scheme of the *feed in* tariff, that was launched in Italy in 2005 [5], the incentive is computed on the basis of the electricity that is actually produced. This scheme is also consistent with the one of Italian Green Certificates [6] for the production of electricity from renewable sources that, fully operational since 2005, is based on the remuneration of electricity from a plant powered by renewable sources (IAFR) in a national market.

The Italian decree 19 February 2007 provides a convenient feed in tariff for the electricity produced by a PV system which varies

between 36 and 49 c€/kW h depending on the size and architectural integration of the system (plants that are small and architecturally integrated are most favoured). This means that the time for return on investment of such plants is around 10 years, and so significantly lower than the one of the expected life time of the photovoltaic module, that is at least 20 years.

Since the incentive is not a subsidy grant, but will be delivered according to the energy produced, a significant sum is initially due (the investment cost of PV can be estimated in Italy between 6000 and 7000 €/kW$_p$, see [7]) and will be repaid over a period of time which is still considered as a medium or long period by economic investors. Finance companies have therefore appeared on the market that install and subsequently operate and maintain large PV plants that require large initial investments. They pay the leasing area to the building owner and collect the money of the financial incentive.

For a comparison between the Italian supporting measures for the electricity production by solar PV and those of France, Germany and Spain see Campoccia et al. [8].

Alongside the incentives, which can be interesting opportunities for private and public investors (as regards the latter, the Italian 2008 Finance Act provides that the facilities for which local authorities are responsible have in any case the maximum feed in tariff), the obligations to install PV systems on new buildings that were introduced by the later legislative requirements should not be forgotten. Following the Italian 2007 and 2008 Finance Acts, any new building in Italy should be equipped with a system that exploits renewable energy for at least 1 kW per residential unit and of this quantity at least 0.2 kW$_p$ per residential unit should be provided by a photovoltaic system.

This legislative incentive to produce electricity from solar energy through photovoltaic conversion has resulted in a steady PV market grow in Italy: at the beginning of 2008 over 7000 systems had been installed by means of the financial incentives, and the power installed was around 10 MW$_p$ per month. This had, and will have much more in the future, a strong land and landscape impact on the Italian territory. To quantify this impact it is possible to refer to some specific parameters of the photovoltaic technology. Assuming between 7 and 10 m^2 the surface necessary to 1 kW$_p$ depending on the type of photovoltaic cell and its conversion efficiency, an increase in the installed capacity of 10 MW$_p$ per month results in an area of PV that is installed every month in Italy between 80,000 and 100,000 m^2.

4. The factors that affect the energy yield and the land use

4.1. The module characteristics

While the PV principle is well known (further details can be found, for example, in [9]), three different generations of PV modules are worth to be identified on the basis of the characteristics of the semiconductor material that is used, because each generation has a different land impact.

The first generation is the one of crystalline silicon cells (monocrystalline and polycrystalline), now widely marketed, that is frequently used in ground mounted PV systems; the second generation is the one of amorphous silicon cells, marketed only few years ago, which have lower conversion efficiencies but are applied where a flexibility of installation is needed; the third generation, currently at the research and development stage, is the one of organic cells (such as photo-electrochemical cells, dye-sensitised cells). As a result of the applications of photovoltaic modules in buildings (BIPV, building integrated photovoltaic), semitransparent photovoltaic cells were developed [10–13] and can be applied as an envelope component that ensures a certain amount of daylight, shades solar energy (thus reducing the space cooling energy need in summer season) and at the same time produces electricity. There are three modes to achieve semitransparency in PV [14]: in some modules semitransparency is induced by a laser removal of portions of material; in others semitransparency is intrinsic as a material property (e.g. in the photo-electrochemical cells and the dye-sensitised cells); in the last modules semitransparency is obtained by simply separating the cells. This results in a large module surface per unit peak power. Also coloured cells [15] were recently marketed: they have slightly lower energy efficiency but are made in various colours and designs.

The possibility to couple semitransparent thin film photovoltaic to solid-state thermoelectric modules (a sort of micro-heat pumps) was also investigated by Xu and Van Dessel in [16] and [17], in order to cool or heat the indoor environment by means of solar radiation converted into electricity that is used by the micro-heat pumps. Finally, two specific equipment that have a great land and landscape impact and that are used to increase the solar energy collected by the module should be mentioned. Motorized movable devices can be used to optimize, as a function of the Sun position, the tilt and orientation of the module; concentration devices that reflect and concentrate the direct solar radiation onto the module can be used to increase the energy collected (a concentration factor is expressed in number of Suns). Both these devices can increase only the direct solar radiation and not the diffuse solar radiation that is a scalar quantity and cannot be intercepted or reflected by mirrors. The gains that can be achieved depend on the climatic characteristics of the site and cannot exceed, in European climates, an increase of the 30% in the solar energy that is collected.

4.2. The system characteristics and the problem of the module orientation and tilt

The effective electricity output of a photovoltaic system depends on the conversion efficiency of the PV cells; on the technical characteristics of the system and on the solar radiation intercepted by the PV module. As regards the first factor, the efficiency of the photovoltaic conversion, which has a theoretical limit of 30%, varies for different types of cells from a lower limit of 4% in the case of amorphous silicon cells to an upper limit of 22% in the case of crystalline silicon cells [34]. Usually monocrystalline or polycrystalline silicon cells are used in practice, with efficiencies between 10% and 15%, and the decision on what cell type should be used in a system may depend on the financial constraints of the project. This is why the cell type is not a design factor that can play a substantial part in increasing the energy yield of the system. The second factor includes all the electrical equipment that carries the electricity from the photovoltaic module to the grid or the end uses in case of stand-alone systems, and includes the BOS (Balance of System), the batteries, and the alternator. Also on this second factor there is a small amount of possibilities of choices. So, the third factor is certainly the most important, because the value of the solar radiation collected strictly depends on the tilt and orientation of the surface module, the geography of the site and the climatic conditions.

It is well known to any PV designer that there is always an optimal module tilt which depends on the latitude (at 46° north latitude this can be found between 30° and 35° if the period of time of analysis is 1 year) and that the optimal module orientation is always south (or north in the southern hemisphere). These optimal tilt and orientation cannot be reached but for the ground mounted systems.

In effect, since the electricity yield of a PV system, and the economic benefit that results from it, strictly depends on the energy collected, it is evident that the preferred tilt of installation of new plants is, at Italian latitudes, the more close to 30–35°.

From this statement it is immediately clear that the installation of PV modules in buildings is particularly problematic because:

- vertical surfaces, for which $\sum = 90^\circ$, the largest in a building, reduce the energy collected compared with the optimal tilt (this reduction is of the order of the 40% for a south orientation and a latitude of 46° N);
- roof surfaces have frequently a tilt angle lower than the optimal one.

In the case of ground mounted systems, on the contrary, with appropriate support structures it is possible to place the module at the optimum tilt angle. The possible reduction in the solar energy received by the module by means of obstructions, of the site geography (especially in mountain areas), and of external (other buildings, trees) or fixed shadings should also be evaluated.

5. Literature review

From the very beginning, the assessment of the environmental impact of photovoltaic has been the subject of numerous studies, which were largely devoted to the energy and environmental impacts, both direct and indirect, but not especially to the territorial and landscape impacts. These studies demonstrated that the environmental impact of the photovoltaic was substantially positive; however this statement was often based on purely energy and environmental considerations. The assessment of the energy viability of photovoltaic technology (that in the past years was accused to require in the production process more energy than the energy produced in its operation) can be found in the studies of Alsema [18,19], confirmed by those of Knapp and Jester [20], who estimated the energy payback time of photovoltaic modules in a range between 2 and 6 years, depending on the technology (polycrystalline silicon or thin film), the solar radiation (from 1100 kW h/m^2 per year to 2200 kW h/m^2 per year) and the type of installation (ground mounted or rooftop). The minimum energy payback time can be obtained in the case of thin films systems, ground mounted plants and with the high solar radiation. As regards the environmental impact in general, one of the first works is the one of Neff [21], who conducted a comparative study among the generation of electricity from photovoltaic conversion, thermal power plants and nuclear power plants. As to the environmental impacts of the photovoltaic technology, Neff lists

- Land use.
- Impact on the climate of the site.
- Emissions of pollutants.

The assessment gives an answer that is favourable to the photovoltaic technology for all the impacts.

Later, the analysis of the environmental impact of photovoltaic was largely conducted by means of life cycle assessment (LCA) techniques [22–29], similarly to what happened to other products and manufacturing processes. This type of evaluation takes into account the production, operation and decommissioning of all components of the plant. In [24] emissions of carbon dioxide per kW_p installed and MWh_e produced are reported as a function of the technology by means of LCA. It is also emphasized that the environmental impact may be reduced in the future as a result of an increase in the conversion efficiency of the cells. This is why other researchers studied the environmental impact of photovoltaic by means of a dynamic approach to LCA [30]. A dynamic approach allows the factors that will make a minor impact of the technology in the future, such as improving the conversion efficiency and increasing the average life time of cells, to be considered. A synthesis by Pacca et al. of different results obtained by various authors can be found in [27]. The impacts of the production and of the disposal of the modules have been extensively studied, and do not have, if not marginally, a relation to the territory. During the production phase there are numerous toxic gases that are used and that, especially in case of accidents, may damage the exterior environment. The disposal stage of a photovoltaic system, which takes place usually after at least 20–25 years of operation, is characterized by the production of the waste of the support structures (usually aluminium), foundations (usually in reinforced concrete) and electric material. The disposal of the silicon modules waste is not particularly problematic; instead the disposal of the CIS modules, and especially cadmium tellurium modules, should be made with great care, for both the environmental danger of the tellurium and the cadmium and their economic value. Less interest was devoted to the study of the photovoltaic impacts related to the land and the landscape, except for the land use impact. Even in studies dealing with the impact of photovoltaic in rural regions, such as the wide and well referenced developed by Varho [31], it seems that these issues are not treated in detail. This may be caused by the fact that in the case of installations in depressed areas and developing countries, energy and environmental benefits are considered dominant, however the urgency for energy savings and resources conservation should not be separated from the land protection. This is especially true in Italy, where wide ground mounted PV plants, the most critical type of plants as regards the land and landscape impact, are spreading rapidly as a consequence of the legislative incentive. The building integrated plants, even if benefit a greater incentive, do not provide an electricity production as profitable as the one of the ground mounted plants.

An environmental impact assessment scheme that addresses also the impacts on the land and landscape can be found in [32], where potential environmental impacts and mitigation measures of various solar energy technologies (central and distributed photovoltaic generation, central and distributed solar thermal, solar thermal electricity generation) are outlined. As regards the photovoltaic, land use, reduction of cultivable land, visual intrusion-aesthetics and impact on ecosystems are reported. The "Guidelines for the identification of potential impacts of photovoltaic systems and for the correct territorial siting" drawn up by the Autonomous Italian Region of Sardinia [33], similarly to what was done by the same Region for wind farms, are a document that addresses the subject of the land and landscape impact of photovoltaic in a comprehensive fashion. These guidelines just represent a response to the growing concerns of regional or local governments and residential communities to the sudden spread of new plants across the territory, particularly the large ground mounted ones that are usually placed in agricultural areas. The Sardinia Region Guidelines, consistently with the purposes of land administration and planning of the document, rather than a description of methodologies to assess the territorial impacts of photovoltaic, contain mainly a set of design criteria (for example the absence of natural areas, historical buildings or historical sites within the 100 m from the plant perimeter) and design requirements (for example the signing of a Recycling Agreement contract with the installation firm) that should be adopted.

6. Definition of impacts

The main territorial and landscape impacts of a photovoltaic system are listed ad analyzed below. This list brings together the information from [33] and other sources that are specified in the following paragraphs, with original content elaborated by the authors.

6.1. Land use

Assuming a tilt of the module of 35°, that is the optimal tilt at Italian latitudes as discussed above, the projected area on the land

is between 6.6 to 8.2 m^2 for kW_p. This value is purely theoretical, since between each row of modules a minimum distance should be ensured to avoid the mutual shading; this can be achieved by respecting the limit distances that can be found in the literature or by performing a detailed simulation by means of a software tool. Passing form the module to the system, literature data report a system area that is about twice the area of the module if expressed in terms of peak power; in terms of energy this area can be quantified as between 28 and 64 m^2/MW h [34] having assumed an appropriate value for the useful life time of the modules and for the solar radiation. It is to be remarked that the land use of the photovoltaic is one of the greatest among the energy technologies [35]. As regards the distributed photovoltaic that is installed on buildings, the soil consumption can be considered irrelevant, since it is included within the building footprint. Some authors have therefore expressed the expectation that before using large land areas to install ground mounted photovoltaics, the area available on the Italian building roofs, that is equal to 47 km^2, should be used first [36].

6.2. Reduction of cultivable land

The medium and large ground mounted systems, if located in previously cultivated areas, represent not only a land use but also a reduction of potentially cultivable land. This impact is also cited by Tsoutsos et al. [32]. The electricity output is therefore likely to be seen as competitive with food production, similar to what happened in the case of energy crops production [37]. In this case, a study conducted by Russi [38], showed that the benefits of a large-scale biodiesel production in Italy would not be enough to offset the costs in terms of land requirements (which implies considerable increase in the food import and in the environmental impacts of the agricultural sector). Also for these reasons the ground mounted photovoltaic systems should be foreseen only if a building integrated installation is not economically nor energy viable.

6.3. Fragmentation of the countryside

This impact, in case of an installation on the ground, refers to the potential loss of the identity elements that are typical of countryside. Even if the site is not a cultivable land, the PV system may deplete the unitary characteristic of a specific countryside. In general, fragmentation is often seen as a negative factor and is opposed to nature conservation, as it is in the case of natural areas, since it causes a decrease of the biodiversity. For these reasons, spatial planning tools tend generally to reduce (or not increase) the fragmentation.

For a general introduction on the topic of landscape fragmentation and land use change dynamics see Nagendra et al. [39]; Jongman in [40] discusses the consequence of fragmentation. While studies on the fragmentation have been developed in the fields of bioscience and agriculture from the late 1990s, only recently the fragmentation is studied, from the residential design scale to the regional development scale, in the field of landscape planning [41].

6.4. Plant degradation

Any existing vegetation may be degraded or removed by the installation of the system. This impact is similar to the previous one but only affects the vegetation. It is interesting to note that in order to limit the impacts 7.2, 7.3 and 7.4 the Guidelines of the Sardinia Region introduce an acceptability criterion for PV systems installed on agricultural land. This criterion is based on the concept of energy self-sufficiency: it is not possible to oversize the PV system for an electricity production beyond the 130% of the local electricity demand. The local electricity demand refers to the "agricultural or industrial utilities on the farmland". This criterion has the merit to promote a sort of distributed photovoltaic power generation and not centralized photovoltaic power generation plants that have a greater territorial and landscape impact and that sometimes are – or can be seen by the local communities – as purely speculative financial investments.

6.5. Visual impact on the landscape

The visual impact on the landscape is an impact particularly critical to be assessed. It is necessary to establish to what extent the PV system affects the perception of the landscape in natural, agricultural or urban areas. To this regard, it is possible to identify compatibility criteria (e.g. use of materials, colours of the modules and structures, visual shields) and assessment procedures based mainly on photographic simulations (*ante operam* pictures and *post operam* pictures with the insertion of the render of the system). In [32] some general design criteria on the mitigation of the visual impact of photovoltaic (e.g. module integrated into the façade of buildings, multi-functional PV facades) are provided, but most of them refer to the building integrated photovoltaic.

In general, there are not many works or case studies that concentrate on the assessment of the visual impact of photovoltaic, and there is a lack of assessment procedures established at an international level. On the contrary, methodologies and case studies on the assessment of the visual impact of wind turbines can be found in the literature, as, for example, the proposed evaluation procedure by Hurtado et al. [42], that that was later applied by Tsoutsos et al. in [43] and the works of Möller [44], Bishop and Miller [45], Torres Sibille et al. [46] and Ladenburg [47]. Also methodologies for the visual impact assessment of new buildings [48] and greenhouses [49] can be found. All these works may serve as a starting point for further research activity on the visual impact of the PV technology.

6.6. Interference with fauna and flora

This impact concerns the possibility of a change in the animal species on the site and in the vegetative life as a consequence of the installation and operation of the system, and can be evaluated through a botanical and faunal study.

6.7. Microclimate change

The impact on the microclimate of the site is essentially due to the temperature that is reached by the PV module during the operation as a result of the heating caused by the infrared component in the solar radiation. The module may reach a temperature equal to 70 °C and this will result in a heating of the air surrounding the system and/or a "discomfort" due to the hot surface of the module. However, it should be considered that the surface temperatures reached by the module are similar to those of any other dark surface receiving the same amount of solar radiation (in fact a photovoltaic panel does not accumulate heat and does not contain a hot circulating fluid such as a solar thermal collectors). Such temperatures may be a problem in the outdoor built environment only when one wants to reach outdoor thermal comfort conditions and avoid the heat island effect. At any rate, the overheating the PV module is avoided, where and when possible, by proper ventilation, as the conversion efficiency decreases for an increase in the temperature of the module (a simple correlation of the PV cell/module efficiency and power as a function of the operating temperature can be found in [50]). A system designed to

properly operate during actual working conditions has also a slight impact on the microclimate of the site.

6.8. Glare

The glare is the temporary loss of vision or reduction in the ability to see the details of the human eye as a result of a (real or imaginary) surface whose luminance at a given point in the direction of the observation exceeds the luminance that can be perceived by the human eye. The reflection of the sunlight by the surface of the photovoltaic module can cause a phenomenon of glare. In this case, the possibility of glare should be assessed if there are potential sensitive receptors (houses, roads, etc.) in the vicinity of the system. To the authors' knowledge no studies that assess this impact exist, and this is the reason why this topic is discussed later.

6.9. Electromagnetic fields

This is the impact of any electrical equipment operating in medium voltage and transforming electricity from low to medium voltage power transmission. In any case, these equipments should be designed and built following the current technical standards in the electricity sector (e.g. the CEI standards in Italy). The Guidelines of the Sardinia Region suggest that the cables in medium voltage and low voltage should be buried in order to decrease the intensity of the magnetic field generated. This seems justified for medium voltage cables, but not for low voltage cable.

6.10. Construction phase impacts

The impacts during the construction of a photovoltaic system are related to the work to build the structures of the system and the connection to the network. These impacts are comparable to those of any other construction site, so they can be mitigated by means of the measures that usually are undertaken to ensure the health and safety in construction sites [51].

7. The assessment of the glare impact from direct sunlight

7.1. Proposal of a procedure for the assessment of the glare impact

Obviously the surface of a PV module is not light reflective, as it is designed to transmit the largest part of the incident solar radiation that is going to be converted into electricity. The module surface is usually a clear glass, which has the highest solar and visible transmittance but still has a solar and visible front reflectance of about 0.1 for normal incidence. At incident angles higher than 60° the reflectance is no more independent from the incident angle and increases up to 1 for an incident angle of 90°. The quantity of light that is reflected form the surface is therefore dependent on the light incident angle.

Surface reflection properties of PV modules were previously studied in order to assess the losses in the solar energy collected: this is the case of Sjerps-Koomen et al. [52], later followed by Yamada et al. [53] that estimated the reflection losses according to the Fresnel's law by the optical modelling of a four-layer encapsulated module. Both these studies have reported a reflection losses of the order of the 5% on the energy collected.

Since there is a beam reflection of the direct sunlight, it is possible that the reflected beam interferes with a sensitive receptor and causes a discomfort glare or a disability glare. This effect is more likely to be encountered in case of opposite hillsides or mountain sites, where the PV system is installed on one side of the hill (usually the one facing south) and on the other side of the hill there are possible receptors (e.g. residential buildings or motor roads).

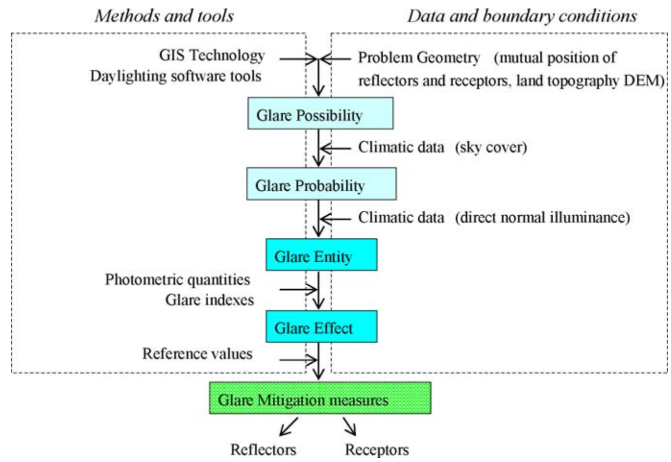

Fig. 1. The glare risk assessment flowchart.

Since no previous literature studies were found on this subject by the authors, in this paper a procedure for the assessment of the glare risk of a ground mounted photovoltaic system is defined. The main steps of this procedure are outlined in Fig. 1. On the left side of the figure methods and tools that can be used to assess this impact are outlined, while on the right side of the figure the various data and boundary conditions that must be provided are reported.

First, the assessment of the glare risk implies the definition of a geometrical problem that strictly depends on the morphology of the land and on the position and size of the PV modules. To determine the mutual position of reflectors and receptors and the land topography, a Digital Elevation Map (DEM) file and a GIS software can be employed. Simple analyses to draw preliminary considerations can be performed by the use of the Sun chart of the site. Then, the geometrical features of the problem may be used to calculate the direction of the reflected beams by means of reflection matrixes and optical geometry laws or may be inputted into a 3D computer graphic software for lighting calculations that is able to predict and visualize the path of the reflected beam.

This first step of the evaluation only assesses the possibility of incurring in a glare effect from a geometrical point of view; the probability of the glare effect can afterwards be identified by combining the information on the possibility of glare with the actual typical sky cover of the site. This, if performed for the entire year with a sufficiently small time step, allows the glare probability to be determined.

The information on the glare probability is however not sufficient to be used in a complete assessment procedure: to evaluate the glare entity and effect on human vision form a quantitative point of view, photometric quantities that are used in lighting design and visual comfort should be used. Then the quantitative results can be compared with reference values in order to evaluate the impact. On this basis, also the appropriate mitigation measures that may be taken to limit the glare both at the reflectors side and at the receptors side can be evaluated. The main problem at this stage is that no glare indexes and reference values adapted to this particular case, seem to be covered in the lighting and visual comfort literature.

7.2. Case study description

The photovoltaic system that is the object of the application of the glare risk assessment procedure presented in Section 7.1 is to be built on the south side of a medium slope hill (~20°) on the territory of the Revigliasco d'Asti commune (Figs. 2–4). 3085 photovoltaic modules rated at 230 W_p and of the size 1.65×0.98 m (specific surface 7 m^2/kW_p) will be installed. The

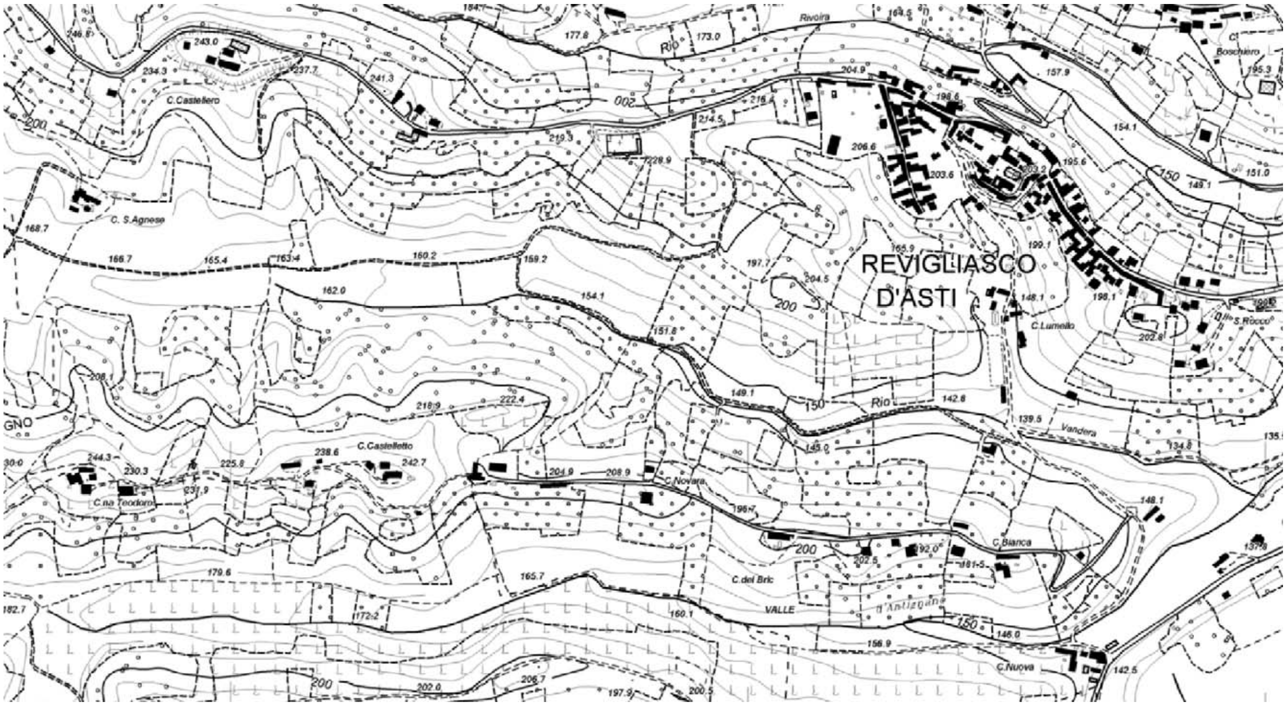

Fig. 2. The territory of the Revigliasco d'Asti commune (out of scale).

tilt of each module is equal to 34° and the orientation is equal to 28° towards west.

An altimetrical digital model of the terrain was created from the DTM of the Piedmont Region; the surfaces of the photovoltaic modules and the volumes of the receptors were placed on the digital model of the terrain on the basis of the vector map (CTR) of the Piedmont Region (2005 Update).

The PV system is modelled into 16 continuous surfaces, containing approximately 192 modules each. The distances between the rows are included in the surfaces.

The receptors that were considered are the followings: the north facades of the buildings placed on the hillside opposite to the PV system and the public road on the peak of the hill in front of the PV system. More than the buildings that are in front of the system (in Fig. 2 the farms Castelletto, Teodoro, Novara, Bianca and all their additional buildings) also the buildings that are placed on the west side of the system (the farms S. Agnese and Castellero) were modelled as possible receptors of the reflected beams in the case of low solar height and positive solar azimuth (east). To avoid any confusion in the discussion of the results, the receptors placed on the opposite hillside will be called ''receptors A'', and the receptors placed on the west side of the PV system will be called ''receptors B''.

The road was modelled as a surface perpendicular to the roadway and passing through the centre line of the roadway, with a height of 2 m from the ground, to represent the glare possibility of an observer driving a car.

The digital terrain map and the reflectors and receptors are reported in Fig. 5.

7.3. The assessment of the glare possibility: the use of Sun charts

Preliminary considerations about the glare risk can be made by using a Sun chart of the particular latitude of the site, as the one

Fig. 3. View of the PV site hill (on the foreground) and of the opposite hillside (on the background).

Fig. 4. Another view of the hillside opposite to the one of the PV system.

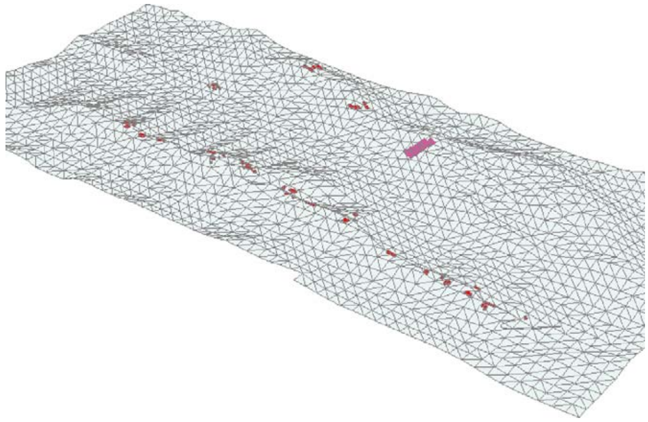

Fig. 5. Aerial view of the digital terrain model with reflectors and receptors.

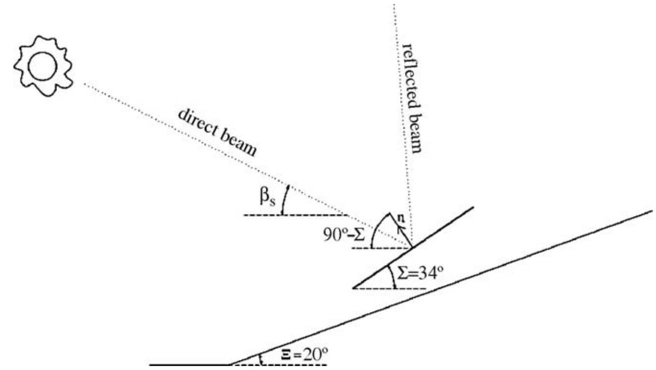

Fig. 7. Vertical section of the generic PV module.

reported in Fig. 6. The Sun position can be identified by means of two angles: a solar altitude β_S which is the vertical angle up from the horizon, and a solar azimuth Φ_S, which is the horizontal rotation angle from south (positive towards east). In a polar Sun chart, as the one represented in Fig. 6, solar altitudes are the concentric circles and solar azimuths are the radiuses.

As can be seen in Fig. 7, which represents the generic section of a PV module that has a tilt equal to $\sum$, the angle between the normal n to the module surface and the horizontal is equal to $90^\circ - \sum$. For the optical geometry laws, a solar altitude angle lower than the angle between the normal to the PV surface and the horizontal, that is

$$\beta_S < (90^\circ - \sum)$$

is sufficient to assure that the beam is reflected toward the sky only if the Sun is in front of the vertical projection of the PV module. This happens when

$$|\Phi - \Phi_S| < 90^\circ$$

that for the case study, which has a surface orientation equal to 28°, means a solar azimuth that falls between 118° and 62° (that is the hatched area on the Sun chart of Fig. 6).

This means that for all the Sun position that falls within the hatched area of the Sun chart of Fig. 6, and for $\beta_S < 56^\circ$, the reflected beam lies in the quadrant opposite to the one of incidence and therefore does not interfere with any receptor.

On the contrary, the possibility of an interference of the reflected beam with the receptors exists for the condition

$$|\Phi - \Phi_S| > 90^\circ \text{ and } \beta_S > 56^\circ$$

which is limited to some midday hours from April to August, and is represented in the Sun chart of Fig. 6 with a dotted hatch, and for the condition

$$|\Phi - \Phi_S| > 90^\circ$$

which is limited to early morning hours of all the months but November, December and January.

In particular, in the first case the reflected beam lies on the quadrant opposite to the one of incidence and may interfere with a receptor of the type A; in the second case, if $|\Phi - \Phi_S| > 90^\circ$, the solar beam is reflected in a direction that may interfere with a receptor of the type B.

By the use of a Sun chart it is possible to define the Sun positions that, from a geometric point of view, are critical and that can be worth of a further detailed study.

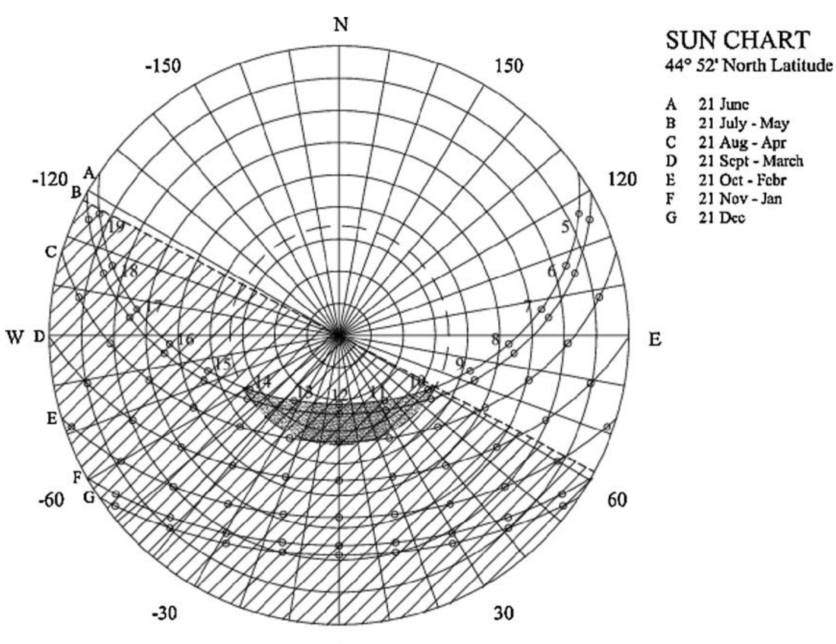

Fig. 6. Sun chart of the site of the case study.

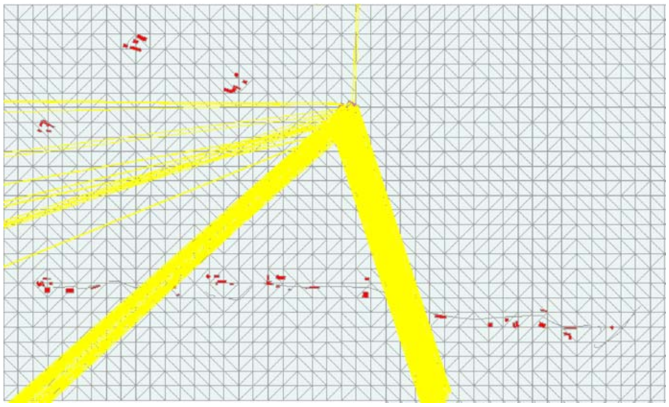

Fig. 8. Horizontal projection of the digital virtual model and the reflected beams (21st July, 12 h time condition).

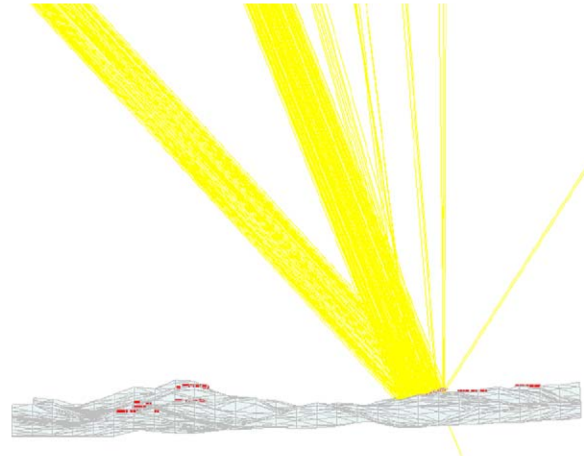

Fig. 9. Vertical projection of the digital virtual model and the reflected beams (21st July, 12 h time condition).

7.4. The assessment of the glare possibility: the use of a lighting calculation software tool

The model of the digital terrain map, together with the reflectors and receptors, was imported into a 3D computer graphic software for lighting calculations in both indoor environments and open spaces, where it is possible to visualize the Sun path and determine the shadows of the objects in the model for each time step of the year. It is also possible to visualize the direct solar beams and the path of the reflected beam once that a particular surface is tagged as a reflector. To determine the Sun position the geographic coordinates WGS84 of the site (latitude 44°52′; longitude 8°9′) were inputted. Since the software tool allows the Sun position and rays to be determined at whatever time and day of a year, the choice of an appropriate time step was done: the reflected rays position was determined for each hour of the 21st day of the December, January, February, March, April, May and June months. The condition of 21st day of the July, August, September, October and November months can be regarded as similar to the one of the May, April, March, February and January months respectively with reference to the Sun position and were not investigated.

The assessment of the glare possibility can be made by means of the visualization of two projections of the model and the reflected beams, e.g. a horizontal (Fig. 8) and a vertical (Fig. 9) projection of the model. From the interpretation of the two projections together, it is possible to determine the direction of the principal reflected beams of light in the 3D space and, in relation to the terrain morphology, it is possible to ascertain whether there is or not a glare possibility.

7.5. Results

As a result of the analysis of the projections for all the days considered, that is not reported here for lack of space, it can be stated that throughout the year there is not any glare possibility for the receptors A. On the contrary, as regards receptors B, a glare possibility can be identified in some of the conditions that fall within the case $|\Phi - \Phi_S| > 90^\circ$, in particular from 8 h 30 to 8 h 45 for the 21st February and from 8 h 15 to 8 h 30 for the 21st March (Fig. 10), because the reflected beam is directed towards the nearest receptor on the west side of the PV system. However these conditions last for a very short time and do not cause a particular glare effect because, at those times, the solar radiation is weak and the direction of the reflected radiation is merely the same of the direct radiation.

Finally, for the receptors that are placed in front of the PV system there is not a glare possibility, while only one of the receptors that are placed on the west side of the PV system is subjected to a minor glare possibility that, for the reasons stated above, seems negligible and was not further investigated in quantitative terms as outlined in Section 7.1.

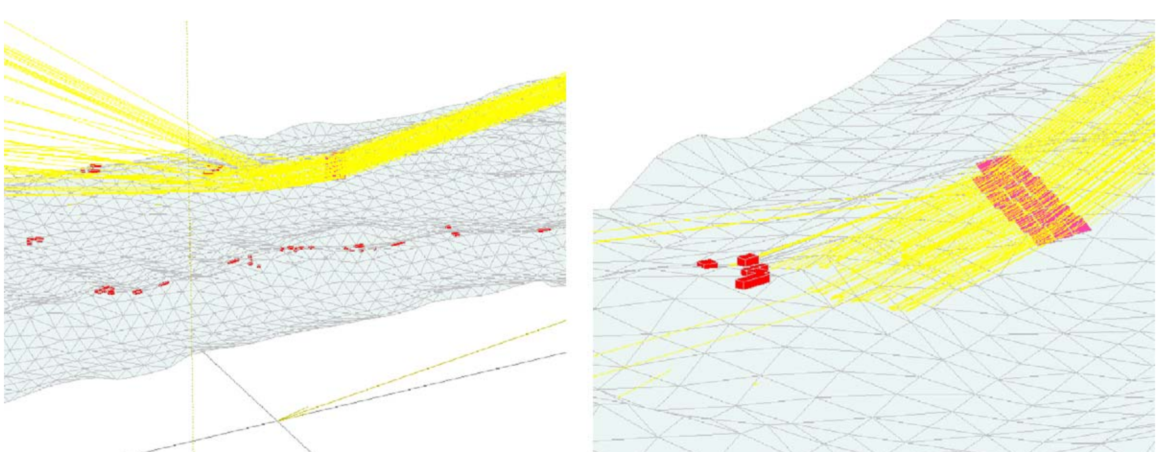

Fig. 10. Two aerial views of the 21st March, 8 h 15 time condition.

8. Conclusions

Having observed both a strong growth of photovoltaic installations, following the Italian governmental financial incentive, and an increasing demand for landscape protection and sustainable development, in this work a contribution on the definition of the territorial impact of the photovoltaic technology is provided.

This issue seems not enough addressed in the literature. There are in fact specific regulations drawn up by local authorities that try to govern this phenomenon, but many of the problems involved by the installation of large ground mounted PV systems are still difficult to be addressed. This is why a comprehensive definition of these impacts is provided. In the second part of the paper the glare from direct sunlight reflection is treated, both from a theoretical point of view and from the evidence provided by an application to a case study. The glare impact strictly depends on the problem geometry of the individual case study and after general considerations, the impact assessment can be made only by performing detailed calculations based on the optical geometry laws, usually by a daylighting software. By the way, among the problems encountered in this impact assessment, the importation of the digital terrain map (DTM) file inside the lighting simulation software and the construction of the receptors and reflectors geometry should be mentioned first. As in any other modelling activity, is also extremely important to define the conditions for the simplification of the problem that best suit the representation of the real case. To avoid, especially in case of large installations, the opposition of local communities, it is desirable that research activities such as the one presented are able to provide designers and validation functionaries of the local administrations with the most advanced and reliable procedures and tools to assess the territorial and landscape compatibility of photovoltaic systems.

This work tries to give a first answer to this problem and concentrate on a specific impact, but further research activity can be identified in the methodologies to quantitatively assess the glare impact (which involves the competences of specific lighting researchers and the need of experimental measurements campaigns), in the application of mitigation measures at both reflectors (e.g. diffusive reflection coatings) and receptors (e.g. plant shadings), and in the visual and aesthetic impact assessment of both large ground mounted photovoltaic and building integrated photovoltaic systems.

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